A New Dark Matter Tool in the LHC era

K.C. Kong
University of Kansas

In collaboration with:
J. Alwall, M. Backovic, (O. Mattelaer), M. McCaskey

Santa Fe 2012 Summer Workshop

"LHC Now"

July 9 - July 13, 2012

MadDM: Dark Matter Calculations using MadGraph 5

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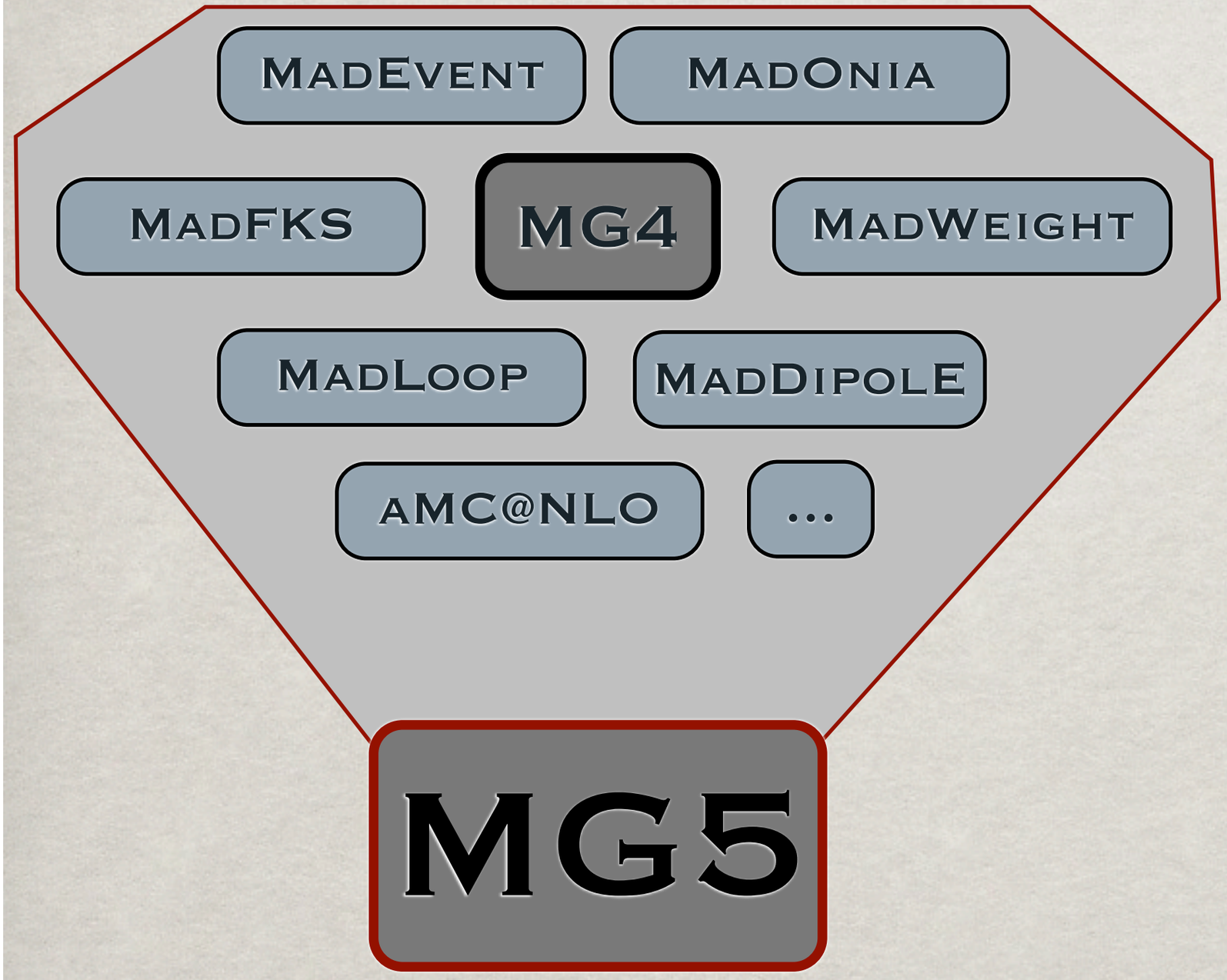
What's Next?

- Measure properties
- Are there more?
- Next stop might be Stop
- Perhaps signals with missing transverse momentum and dark matter
- A good news is that
  - experimentalists are working hard
  - theorists are providing interesting ideas
  - excellent tools have been developed!

A bit of history



1994 Core MG4

2002 MadEvent

2007 MadDipole

2008 MadOnia

2008 MadWeight

2009 MadFKS

2011 MadLoop

↓

2011 MG5

One code, to rule them all!

A slide made by V. Hirschi for TOOLS 2012 workshop

MadGraph 5 Specs

- High-level language: Python
  - Complex data-structures allow for very general objects while keeping speed where needed.
  - Involved algorithms => Performance increase
- Built-in testing suite => Reliability
- User-interface and automatic doc. => User friendly
- Flexible and Modular => Developer friendly
  All-in-one distribution

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Supported Models

Color Code

New and in the public release!

Planned / Ongoing progress

Done and will be made public for **MG5 v2.0**

Effective Theories	N-Legs vertices, vN
color structures	Sextets, ε^{IJK}, virtually ALL
Lorentz Structures	ALL, thanks to Aloha
Spins supported	1, 1/2, (3/2), 2
Gauges	Unitary, Feynman
Complex Mass Scheme	Automatic Model Conversion Available for NLO too!
Model with loop info	Import UFO Loop-models
Decay widths computation	On-the-fly widths computation

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Diagram Generation
speed benchmark

Process	MadGraph 4	MadGraph 5	Subprocesses	Diagrams
$pp \to jjj$	29.0 s	25.8 s	34	307
$pp \to jjl^+l^-$	341 s	103 s	108	1216
$pp \to jjje^+e^-$	1150 s	134 s	141	9012
$u\bar{u} \to e^+e^-e^+e^-e^+e^-$	772 s	242 s	1	3474
$gg \to ggggg$	2788 s	1050 s	1	7245
$pp \to jj(W^+ \to l^+\nu_l)$	146 s	25.7 s	82	304
$pp \to t\bar{t}$+full decays	5640 s	15.7 s	27	45
$pp \to \tilde{q}/\tilde{g}\,\tilde{q}/\tilde{g}$	222 s	107 s	313	475
7 particle decay chain	383 s	13.9 s	1	6
$gg \to (\tilde{g} \to u\bar{u}\tilde{\chi}_1^0)(\tilde{g} \to u\bar{u}\tilde{\chi}_1^0)$	70 s	13.9 s	1	48
$pp \to (\tilde{g} \to jj\tilde{\chi}_1^0)(\tilde{g} \to jj\tilde{\chi}_1^0)$	>> 10^7 years	251 s	144	11008
$gg \to (\tilde{g} \to u(\bar{\tilde{u}}_l \to \bar{u}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0)))(\tilde{g} \to ud\tilde{\chi}_1^-)$				

Very fast decay chains opening the way for new types of processes!

MadEvent5 now able to handle such large decay chains.

A slide made by V. Hirschi for TOOLS 2012 workshop

Event Generation
speed benchmark

Generation of 10,000 unweighted events
Computer: Sony Vaio TZ laptop / *128-core cluster

Process	Subproc. dirs.		Channels		Directory size		Event gen. time	
	MG 4	MG 5	MG 4	MG 5	MG 4	MG 5	MG 4	MG 5
$pp \to W^+j$	6	2	12	4	79 MB	35 MB	3:15 min	1:55 min
$pp \to W^+jj$	41	4	138	24	438 MB	64 MB	9:15 min	4:19 min
$pp \to W^+jjj$	73	5	1164	120	842 MB	110 MB	21:41 min*	8:14 min*
$pp \to W^+jjjj$	296	7	15029	609	3.8 GB	352 MB	2:54 h*	46:50 min*
$pp \to W^+jjjjj$	-	8	-	2976	-	1.5 GB	-	11:39 h*
$pp \to l^+l^-j$	12	2	48	8	149 MB	44 MB	21:46 min	3:00 min
$pp \to l^+l^-jj$	54	4	586	48	612 MB	83 MB	2:40 h	11:52 min
$pp \to l^+l^-jjj$	86	5	5408	240	1.2 GB	151 MB	49:18 min*	16:38 min*
$pp \to l^+l^-jjjj$	235	7	65472	1218	5.3 GB	662 MB	7:16 h*	2:45 h*
$pp \to t\bar{t}$	3	2	5	3	49 MB	39 MB	2:39 min	1:55 min
$pp \to t\bar{t}j$	7	3	45	17	97 MB	56 MB	10:24 min	3:52 min
$pp \to t\bar{t}jj$	22	5	417	103	274 MB	98 MB	1:50 h	32:37 min
$pp \to t\bar{t}jjj$	34	6	3816	545	620 MB	209 MB	2:45 h*	23:15 min*

No problem running pp>tt~jj on a laptop!

A slide made by V. Hirschi for TOOLS 2012 workshop

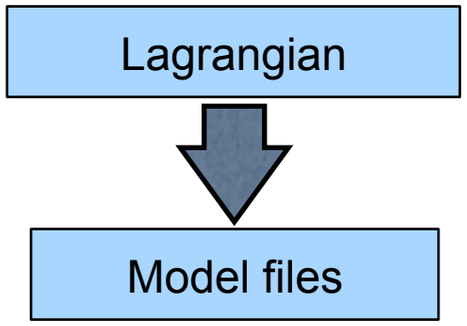
Collider Physics using MadGraph

Collider Physics using MadGraph

Lagrangian

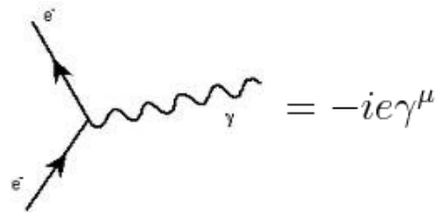
$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + i\bar{\Psi}\left(\not{D} - m\right)\Psi + \left(D^{\mu}\phi\right)^{*} D_{\mu}\phi + \ldots$$

Collider Physics using MadGraph



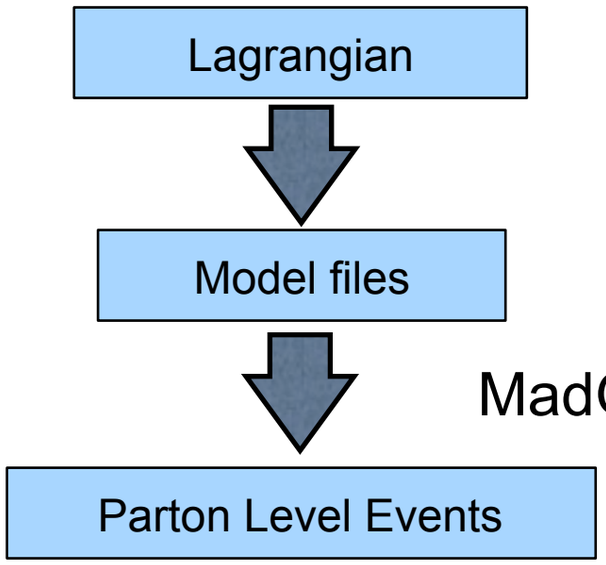
FeynRules

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + i\bar{\Psi}\left(\not{D} - m\right)\Psi + \left(D^{\mu}\phi\right)^{*} D_{\mu}\phi + \ldots$$



$$= -ie\gamma^{\mu}$$

Collider Physics using MadGraph



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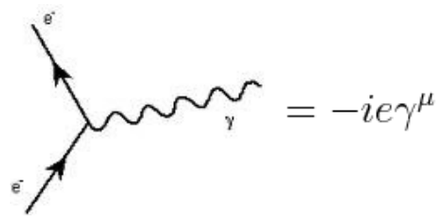
MadGraph/MadEvent



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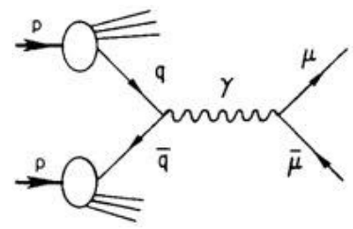

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Lagrangian

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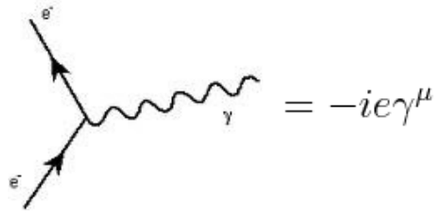
Model files

MadGraph/MadEvent



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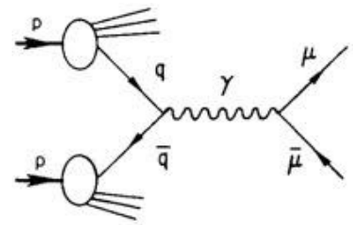
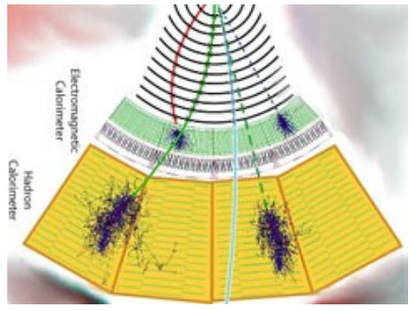


Parton Level Events



Pythia

ISR / Parton Showering

Collider Physics using MadGraph

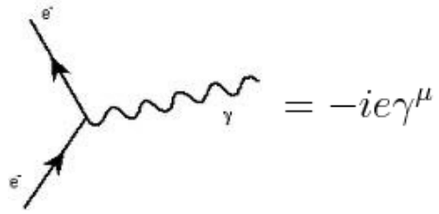
Lagrangian

FeynRules

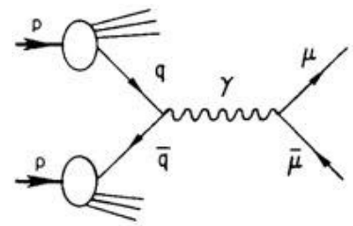
$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + i\bar{\Psi}\left(\not{D} - m\right)\Psi + \left(D^{\mu}\phi\right)^{*} D_{\mu}\phi + \ldots$$

Model files

MadGraph/MadEvent



$= -ie\gamma^{\mu}$



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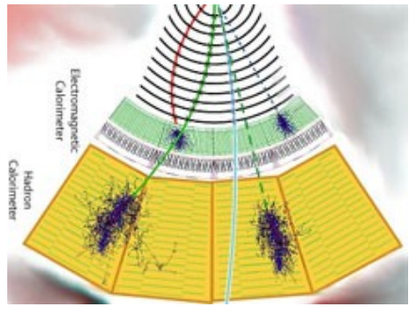


Pythia

ISR / Parton Showering

PGS/Delphes

Jet Reconstruction

Collider Physics using MadGraph

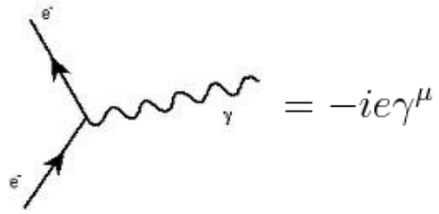
Lagrangian

FeynRules

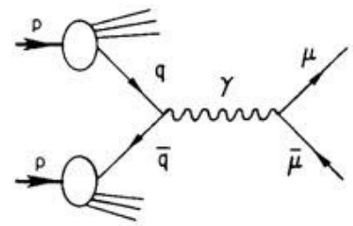
$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + i\bar{\Psi}\left(\not{D} - m\right)\Psi + \left(D^{\mu}\phi\right)^{*} D_{\mu}\phi + \ldots$$

Model files

MadGraph/MadEvent



$= -ie\gamma^{\mu}$



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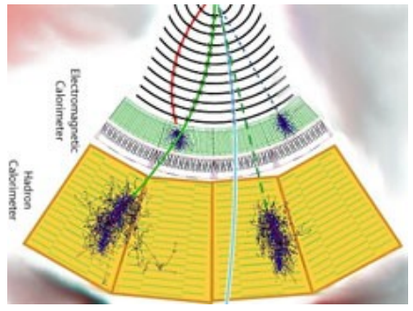

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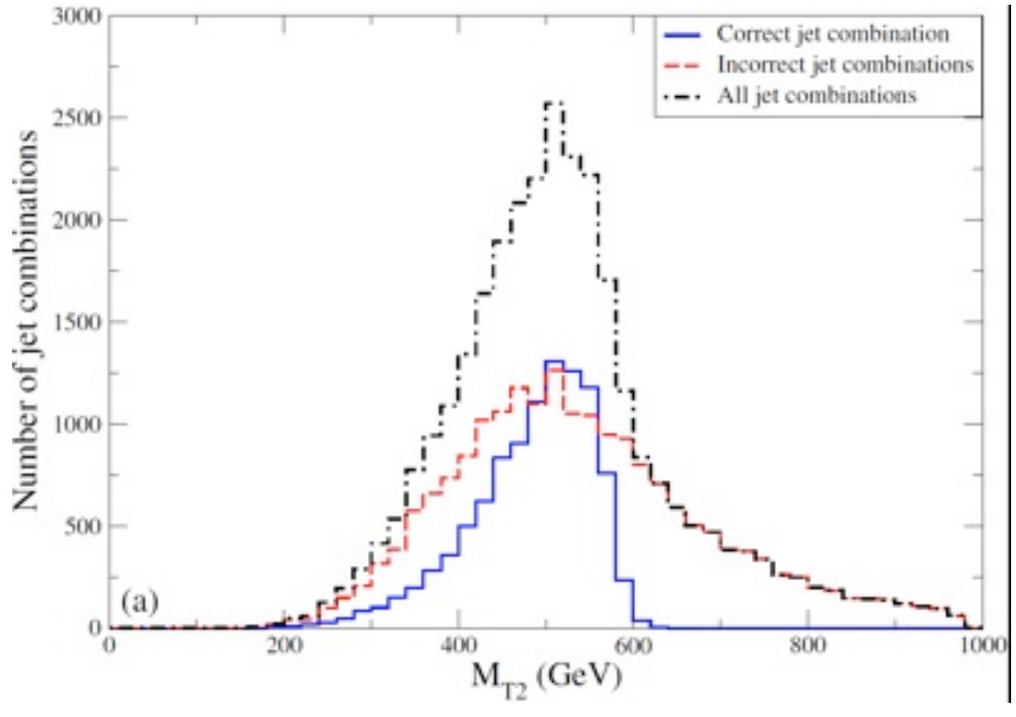
MadAnalysis / ExRootAnalysis



Pretty Plots

Collider Physics using MadGraph

Lagrangian

FeynRules

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + i\bar{\Psi}\left(\not{D} - m\right)\Psi + \left(D^{\mu}\phi\right)^{*} D_{\mu}\phi + \ldots$$

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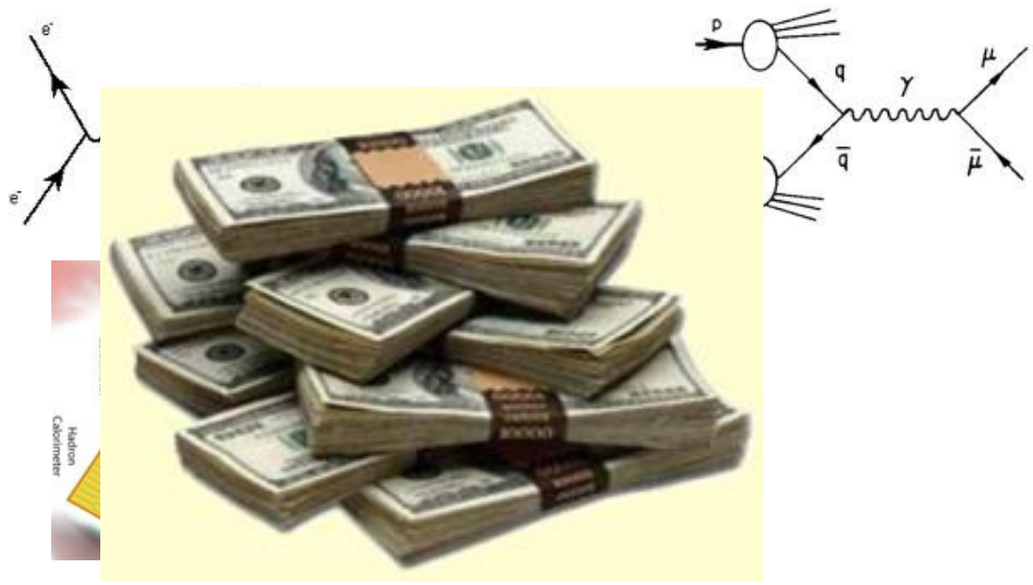
MadGraph/MadEvent



Parton Level Events

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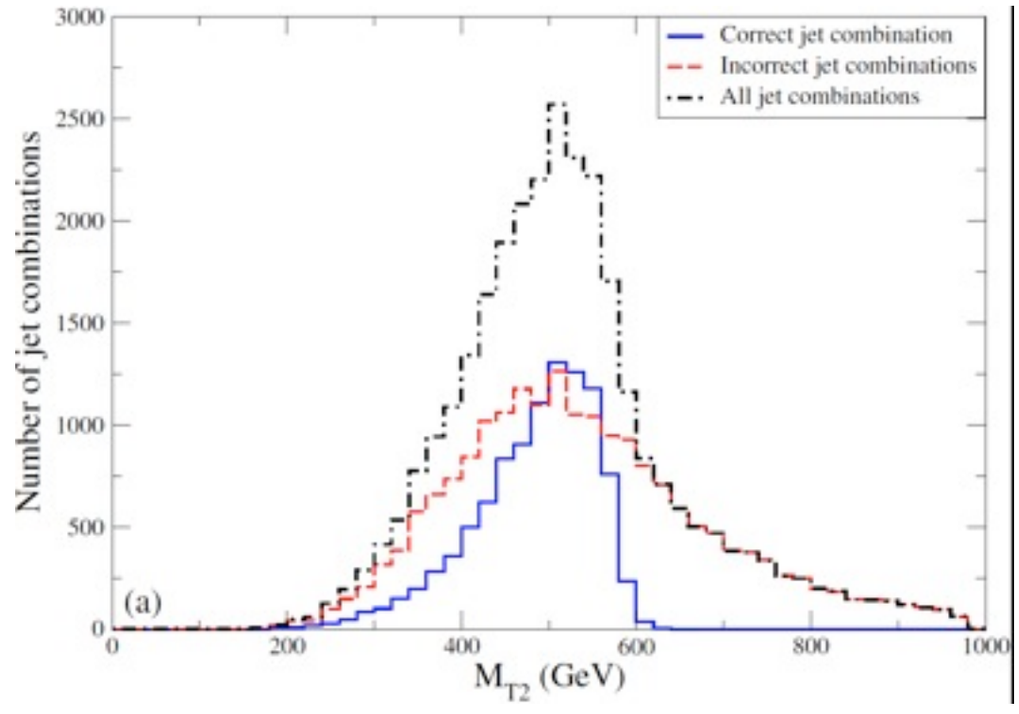
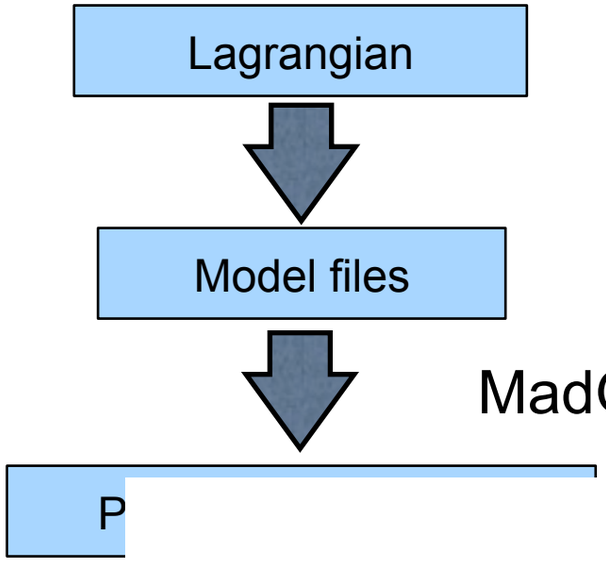


Pretty Plots

Profit

Collider Physics using MadGraph



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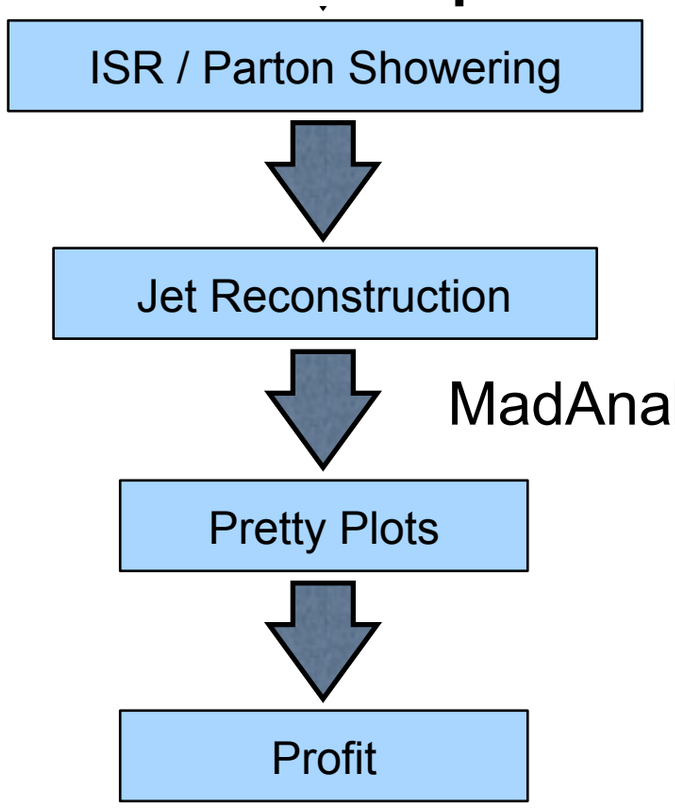
MadGraph/MadEvent

Many other packages such as

MadLoop, MadGolem, MadFKS, MadWeight, MadDipole



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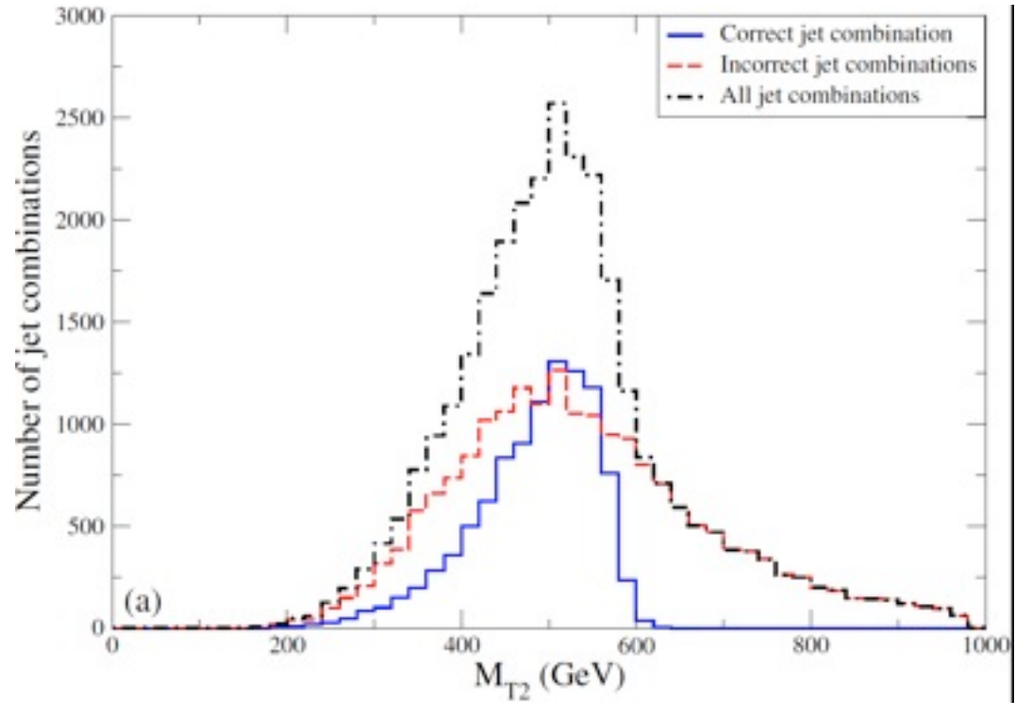
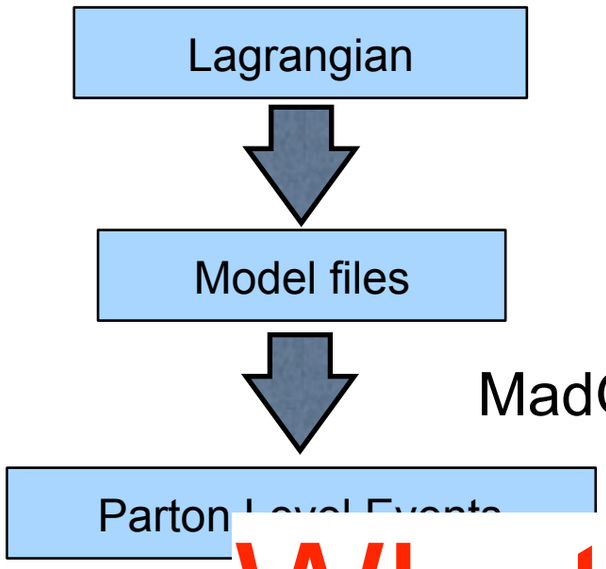


Collider Physics using MadGraph



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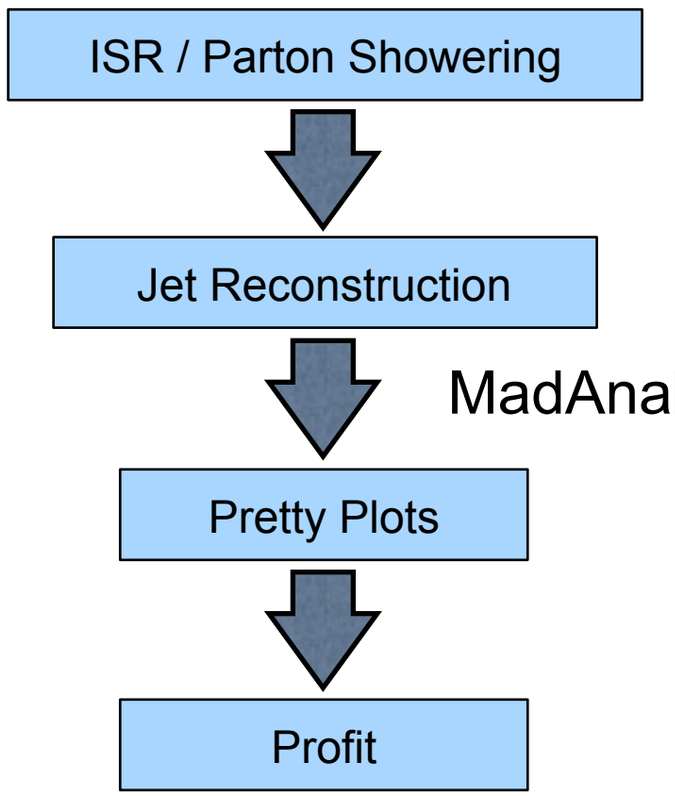
MadGraph/MadEvent

What about Dark Matter?



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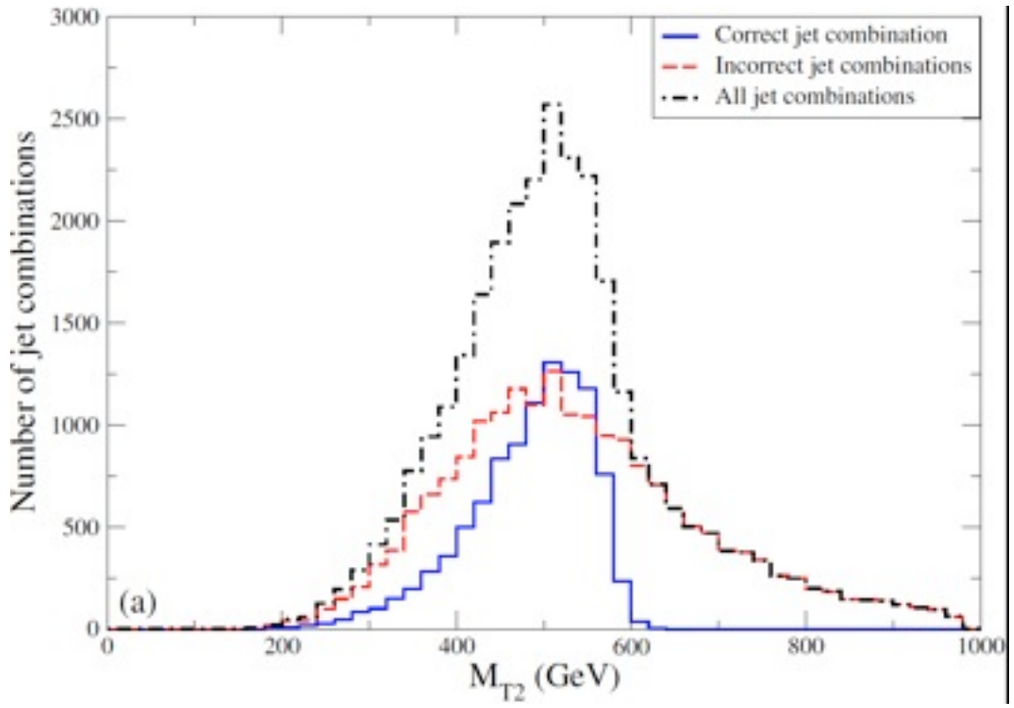

Calculations of DM Density

- Codes that computes relic density (in SUSY)
  - Neutdrive, DarkSUSY, Isatools
  - Many private codes: SSARD, Drees, Roskowski.....
- micrOmegas: generic program to calculate the relic density of DM in ANY model.
  - relic density, direct/indirect detection rate
  - A great tool for DM physics

Why a new DM tool in MG5

- MadDM provides a critical link that is currently missing in today's MG routine. It would complete MG effort.
- It would be most beneficial to be able to simulate collider events while simultaneously taking into account the astrophysical constraints.
- More importantly, MadDM would be more suitable to include higher order contributions in DM physics.
- Users should be able to cross-check existing tools against MadDM.
- Some limitations in micrOmegas and CalcHEP (not critical)
    - 4 point interaction in SU(3) interaction needs a special treatment. FeynRules does not generate correct model files for CalcHEP/micrOmegas. (see LanHEP)

Boltzmann Equation

$$\frac{dn_\psi}{dt} + 3Hn_\psi = -\langle\sigma|v|\rangle(n_\psi^2 - (n_\psi^{EQ})^2)$$

- DM relic density is governed by the expansion of the universe and the pair annihilation or creation that keeps the DM in equilibrium.Transformation to simplify the equation is to use the equilibrium density per comoving volume.Yet another transformation is to use temperature instead of time.

$$\frac{dY}{dx} = -\sqrt{\frac{45}{4\pi^3}}\frac{m_{pl}\ x}{\sqrt{g_*}\ m^2}\langle\sigma_A|v|\rangle s[Y^2 - Y_{EQ}^2]$$

$$Y \equiv n_\psi/s \qquad x \equiv m_\psi/T$$

Thermally Averaged Annihilation Cross Section (TAACS)

Kolb and Turner

$$\langle \sigma_{\psi\bar{\psi}\to X\bar{X}}|v|\rangle \equiv \left(n_{\psi}^{EQ}\right)^{-2} \int d\Pi_{\psi} d\Pi_{\bar{\psi}} d\Pi_{X} d\Pi_{\bar{X}} (2\pi)^4$$

$$\delta^4(p_{\psi} + p_{\bar{\psi}} - p_X - p_{\bar{X}}) |\mathcal{M}|^2 \exp(-E_{\psi}/T) \exp(-E_{\bar{\psi}}/T)$$

Thermally Averaged Annihilation Cross Section (TAACS)

Kolb and Turner

$$\langle \sigma_{\psi\bar{\psi}\to X\bar{X}}|v|\rangle \equiv \overline{\left(n_{\psi}^{EQ}\right)^{-2}} \int d\Pi_{\psi} d\Pi_{\bar{\psi}} d\Pi_{X} d\Pi_{\bar{X}} (2\pi)^4$$
$$\delta^4(p_{\psi} + p_{\bar{\psi}} - p_X - p_{\bar{X}}) |\mathcal{M}|^2 \exp(-E_{\psi}/T) \exp(-E_{\bar{\psi}}/T)$$

$\overline{\left(n_{\psi}^{EQ}\right)^{-2}}$ — The thermal equlibrium density of DM

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The thermal equlibrium density of DM

The matrix element integrated over the final state phase space. Matrix elements can be obtained by Madgraph and in a $2 \to 2$ process can be easily integrated manually.

Thermally Averaged Annihilation Cross Section (TAACS)

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The thermal equlibrium density of DM

The matrix element integrated over the final state phase space. Matrix elements can be obtained by Madgraph and in a $2 \to 2$ process can be easily integrated manually.

After a few pages of algebra and variable transformations, this part of the expression can be written in terms of the center of mass energy of the process, or more conveniently in terms of a relative velocity, beta.

TAACS Simplified

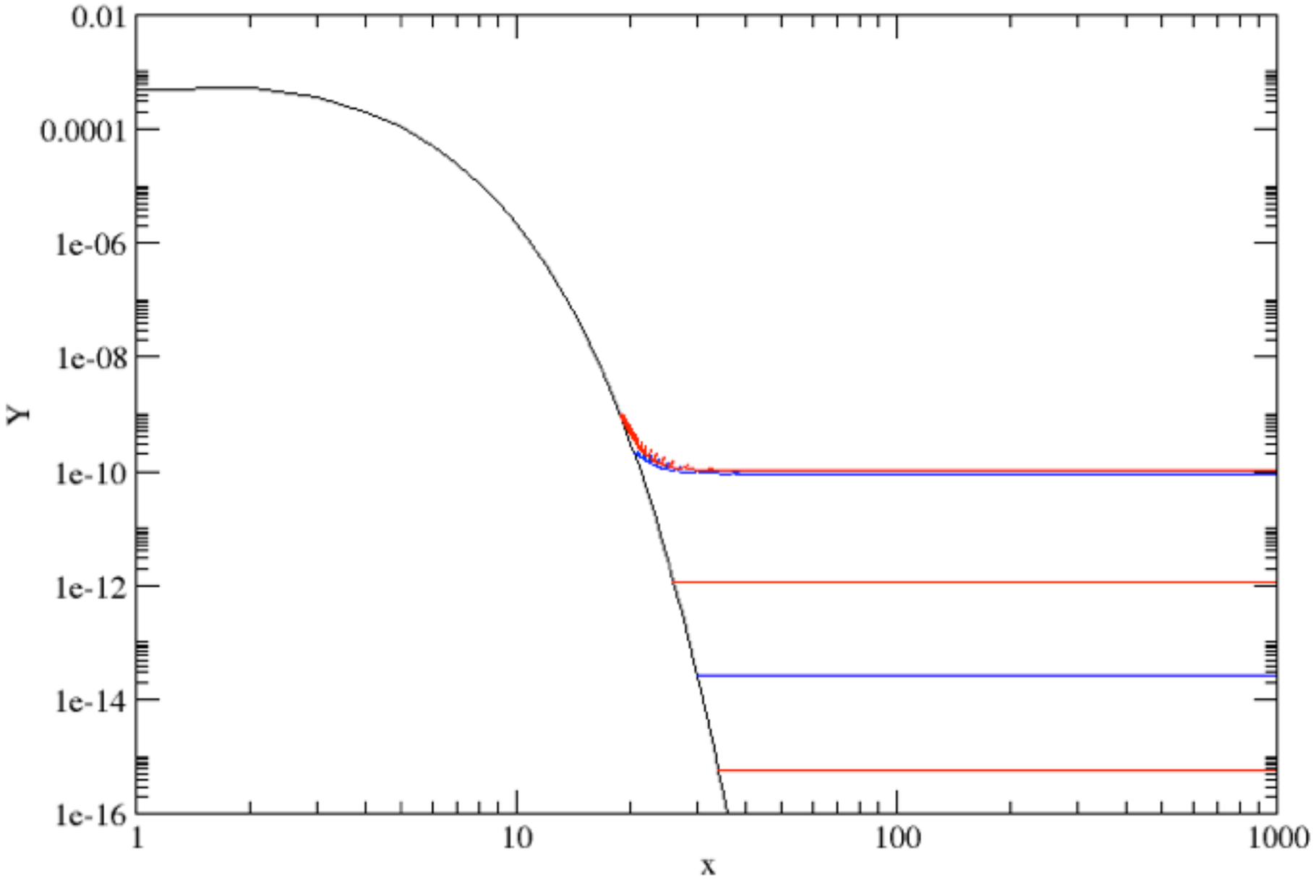
$$\langle \sigma_A |v| \rangle = \frac{x^{3/2}}{m^2\sqrt{\pi}} \int_0^1 d\beta \, \frac{\beta^2}{(1-\beta^2)^{9/4}} \, e^{-2x\left(\frac{1}{\sqrt{1-\beta^2}}-1\right)} \int |\mathcal{M}|^2 dPS_n$$

- Use MadGraph for the matrix element evaluation
- For a 2→2 process the integral over final state phase space is only a 1-D integral.
- Because the evaluation of the matrix elements takes the most amount of time this is evaluated at a limited number of betas and interpolated.
- Leave the option open for exact evaluation in the case of a narrow resonance (takes more time)

Practical Integration of Chemical Rate Equation

- Numerically it is impractical to integrate the Chemical Rate Equation from a small x
- Ideally we would want to start integrating just before the freezeout temperature.
- Since we do not know the freezeout temperature a priori, we start from a large x and work backwards until two solutions match within a certain tolerance
- All the ODE integrations are after freezout, and this process is very fast.

Practical Integration of Chemical Rate Equation

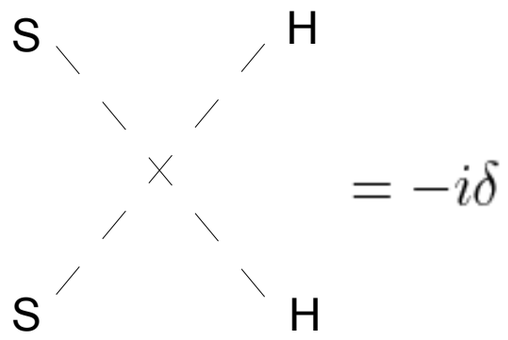


Toy DM Model

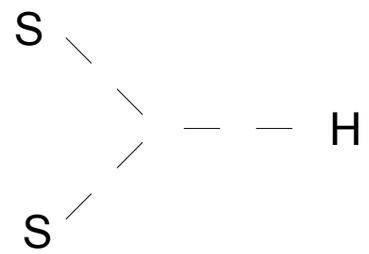
$$V_{\rm DM} = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta}{2}H^\dagger H S^2 + \frac{m_S^2}{2}S^2 + \frac{\lambda_S}{4}S^4$$

- Add a real scalar singlet to the SM
- contains a S → -S symmetry.
- S only talks to the rest of the SM through the Higgs.
- Only two parameters needed to set the DM mass and the interaction stength.
- Higgs mass = 125 GeV
- Implement the model in both micrOmegas and MG5.

Interactions and Diagrams

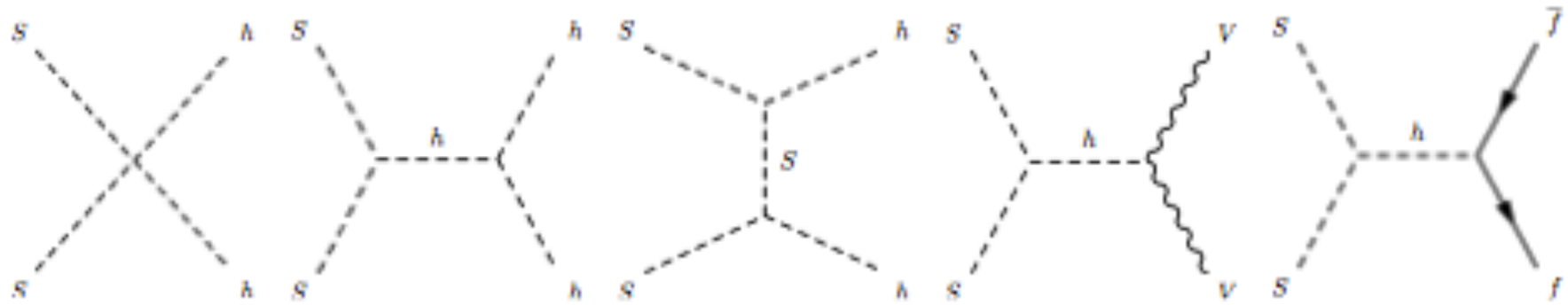


$= -i\delta$

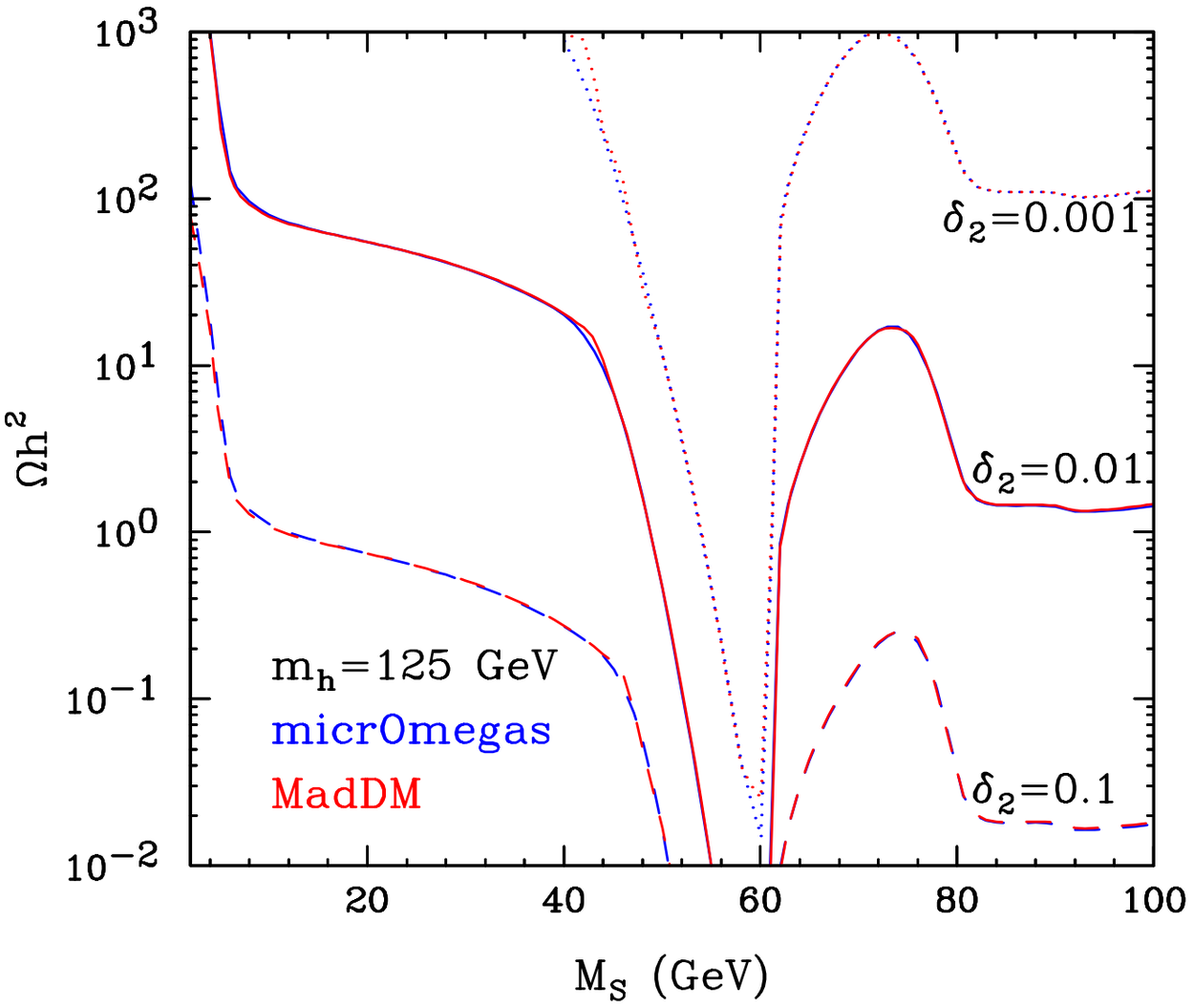


$= -i\delta v$

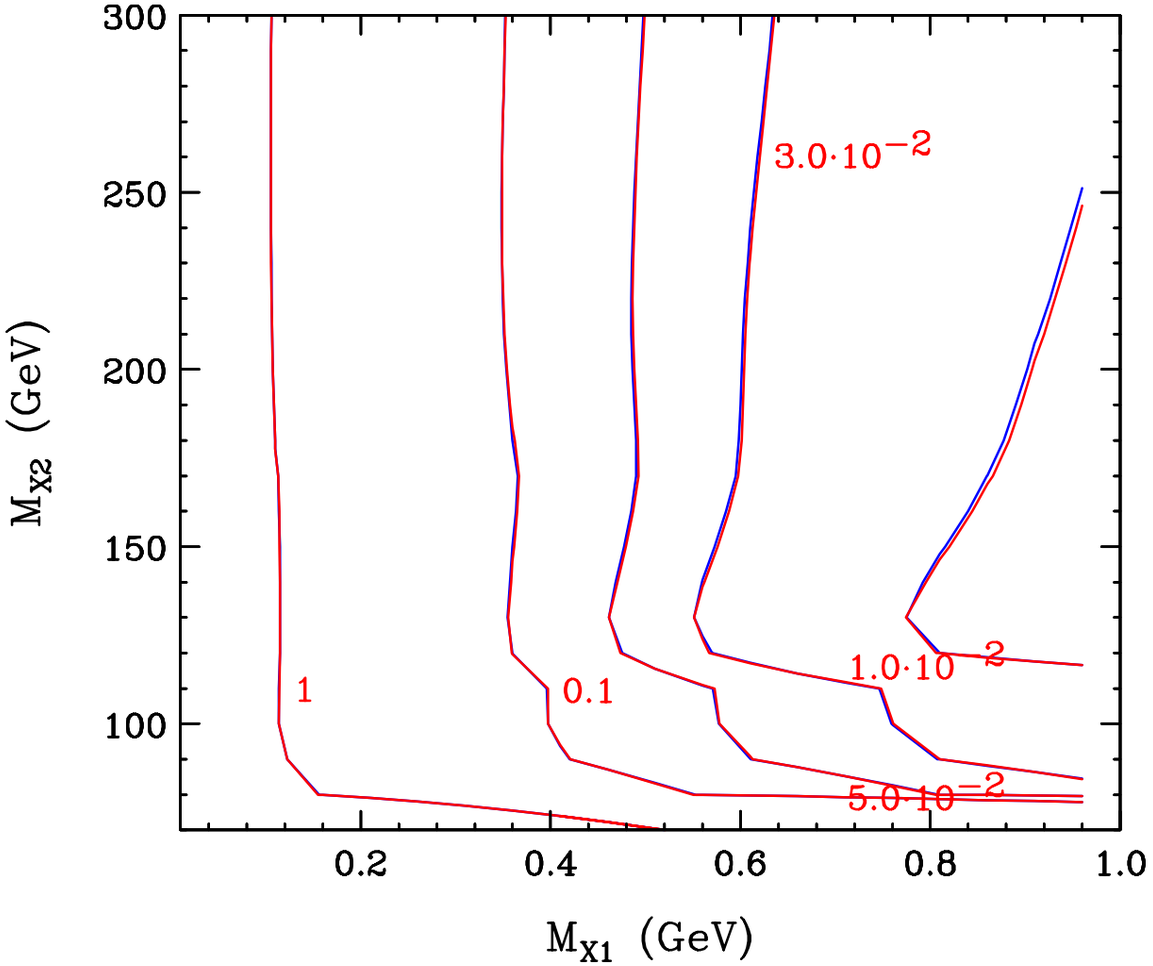
Feynman Diagrams for DM annihilation

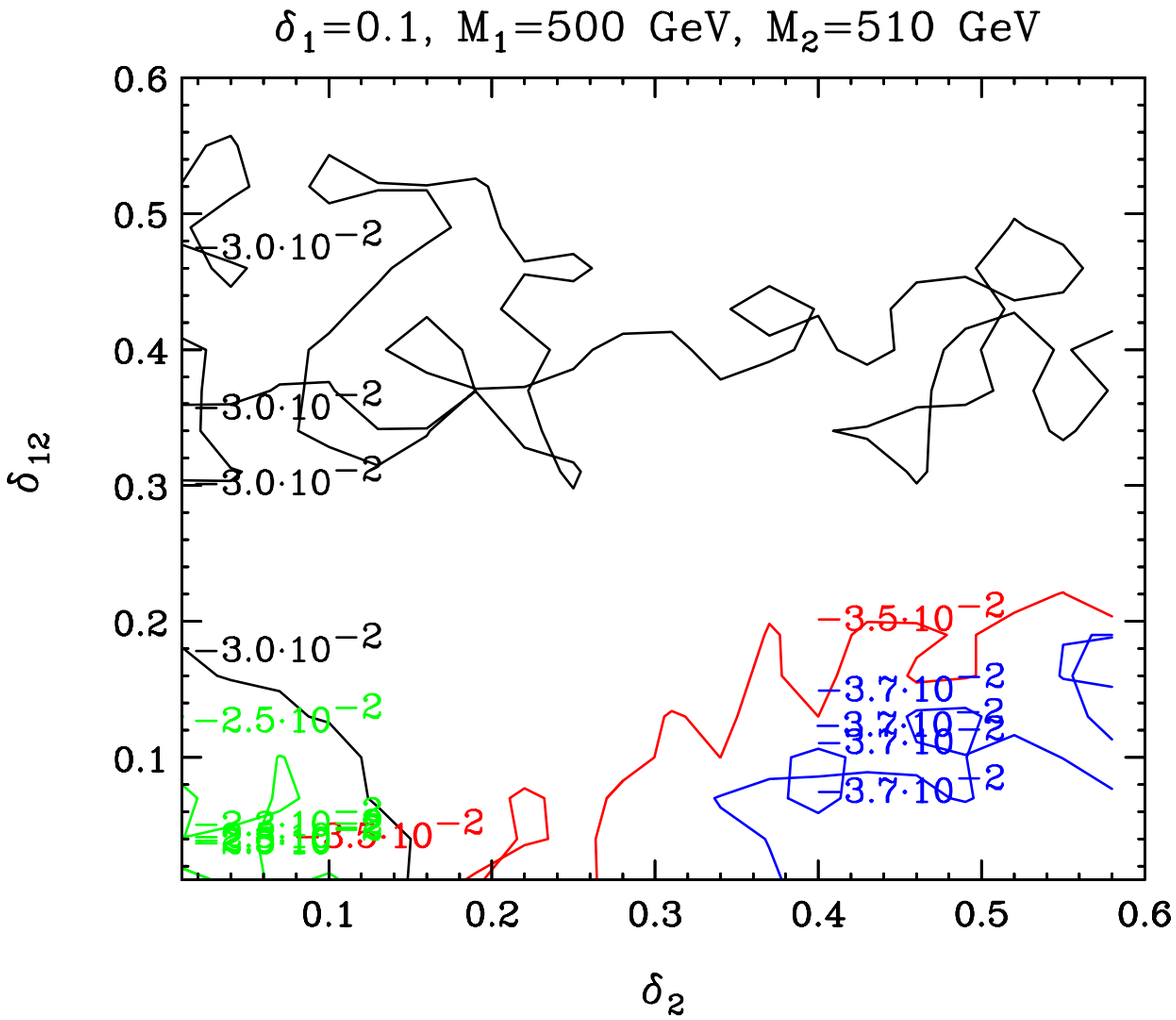


Comparison with micrOmegas (scalar DM)



Comparison with micrOmegas (fermionic DM)





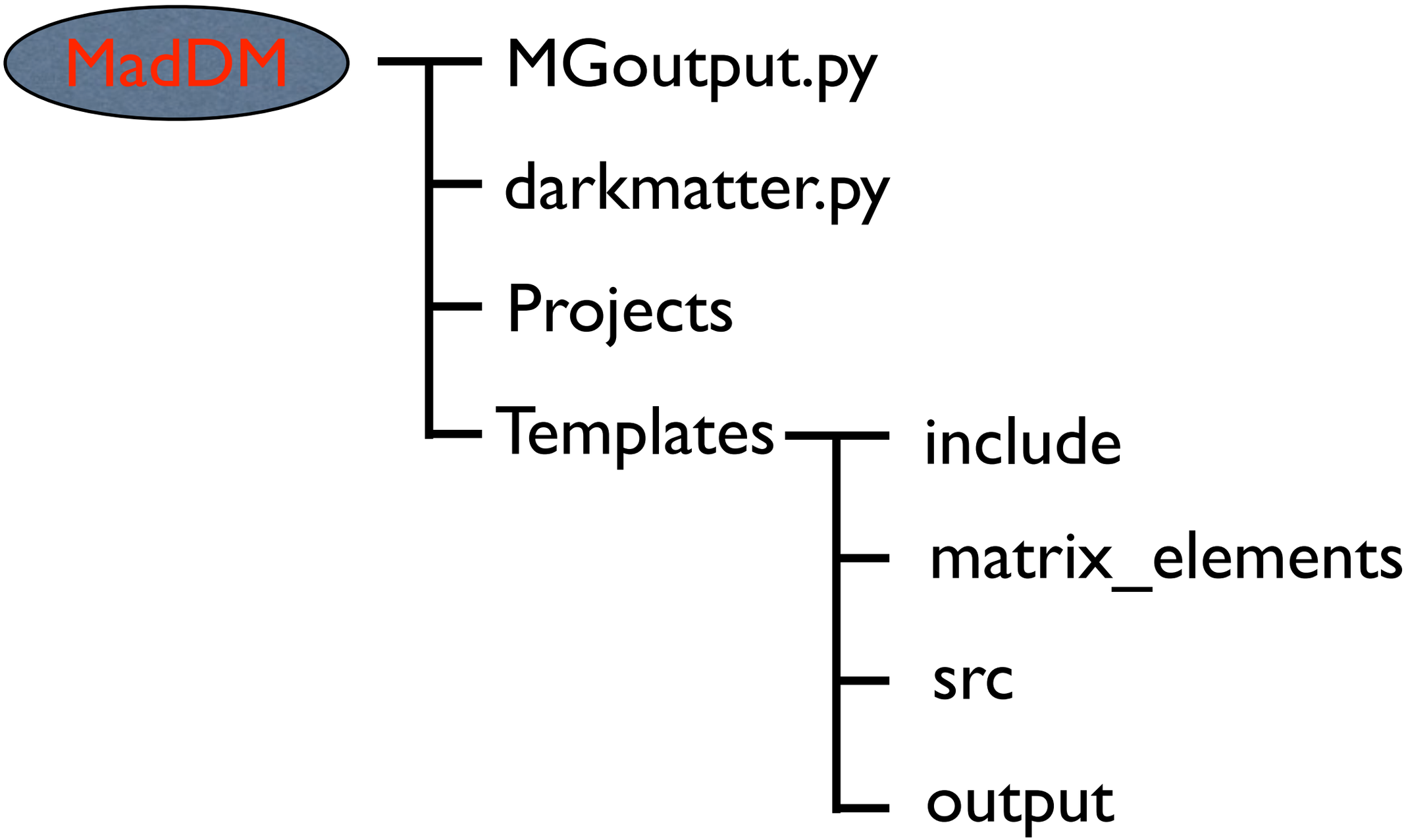
Current Status

- MadDM has a code for Relic density (including coannihilations, correct treatment of resonances and threshold effects)
  - direct/indirect detection to be included
- Cross checked with simple DM models against micrOmegas (scalar, fermion, vector)
- We are validating MadDM for MSSM

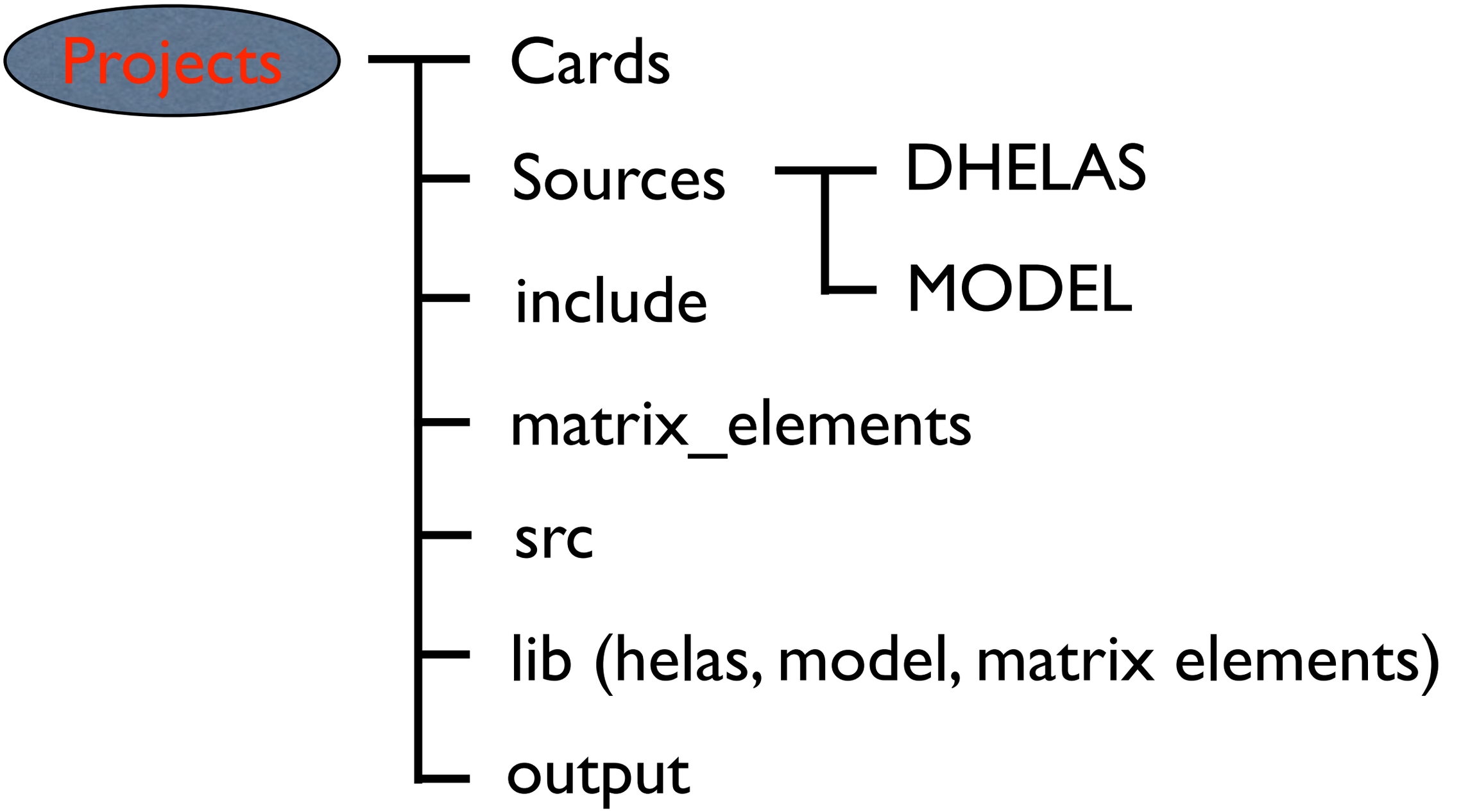
Additional features to be implemented in the future

- Interactive running in MG5 command line
- Web based interface (similar to that of MadGraph)
- Direct and indirect detection
  - link to PYTHIA (and GALPROP?)
- Multi-body final state and beyond leading order
- We want MadDM to be more than a simple DM tool
  - everything related to DM, including experimental data, and missing energy signature at the LHC
  - Your inputs are valuable!

Structure


MadDM
MGoutput.py
darkmatter.py
Projects
Templates
include
matrix_elements
src
output

Numerical Part: Projects



Running MadDM

- Need a model (input) and numerical values of parameters
- Find a DM candidate
- Generate Matrix Elements
- Prepare for numerical session
  - export UFO to MG4 format
  - generate HELAS and necessary model LIB
  - Compile
- Run maddm.x
  - output: relic density, annihilation cross sections, TAACS, Bessel functions, dof, etc

MadDM or something else?

- People who are involved:
  - Alwall, Backovic, Kong, McCaskey
  - What about Olivier?

MadDM or something else?

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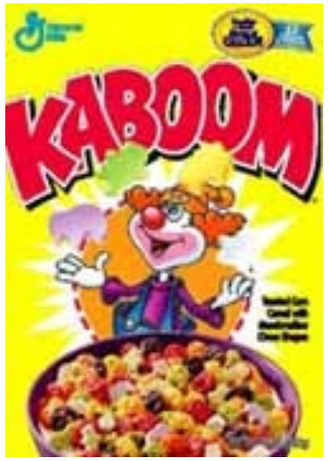
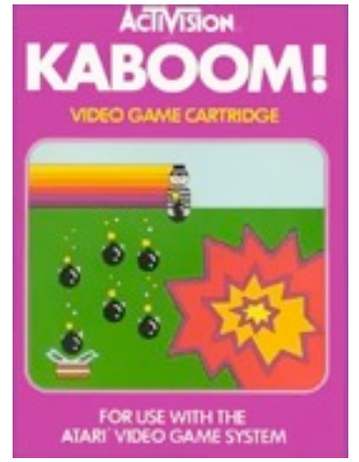
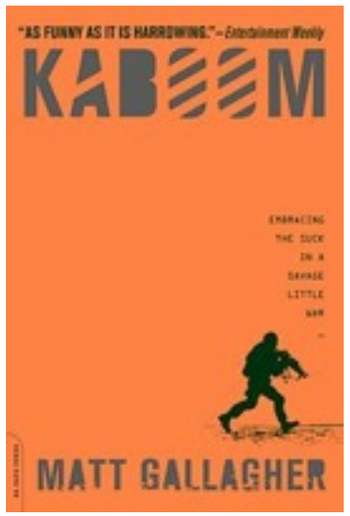
KABOOM?





- Film and television
  - *Kaboom* (film), 2010 film directed by Gregg Araki
  - *Kaboom!!*, a Mexican variety television show
  - "522666" (*kaboom* on a telephone keypad), episode #1-5 of the television series *Millennium*
  - "Kaboom" (*Parks and Recreation*), a second season episode of *Parks and Recreation*
  - Key Atomic Benefits Office Of Mankind (K.A.B.O.O.M.), a fictional organization in the film *The Naked Gun 2½: The Smell of Fear*



- Literature and entertainment
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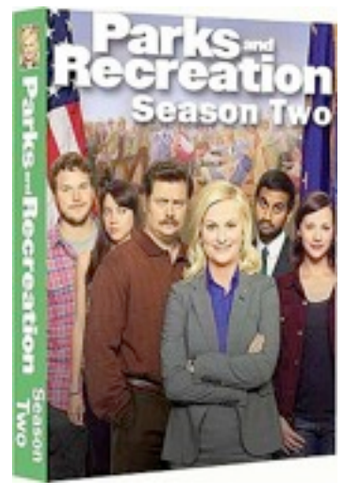
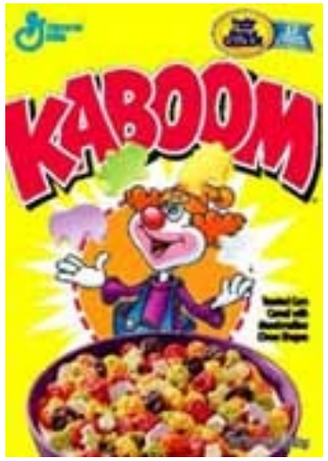
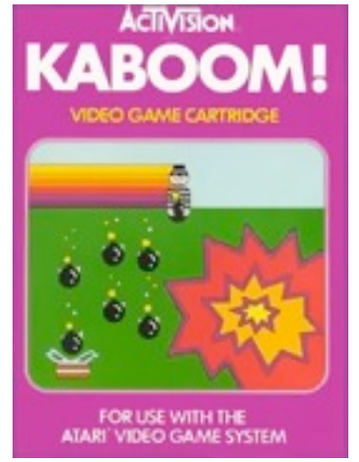
  - KFOG KaBoom, a yearly concert in San Francisco sponsored by KFOG
  - KABOOM!, the first full-length studio album of Chicago rock/pop band I Fight Dragons



- Other uses
  - KABOOM (breakfast cereal), produced by General Mills
  - Kaboom, a tile cleaner manufactured by Church and Dwight
  - Slang for a 3 point shot in Basketball
  - Kaboom, a single-speed bike made by the Kona Bicycle Company
  - Kaboom, is a ginseng performance coffee named Kaboom Kahve
  - KaBOOM!, a U.S. non-profit organization that helps communities build local playspaces for children

KABOOM?





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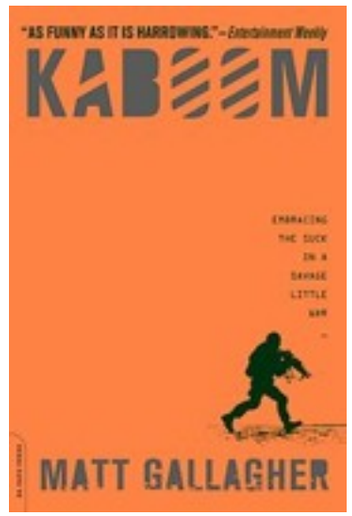

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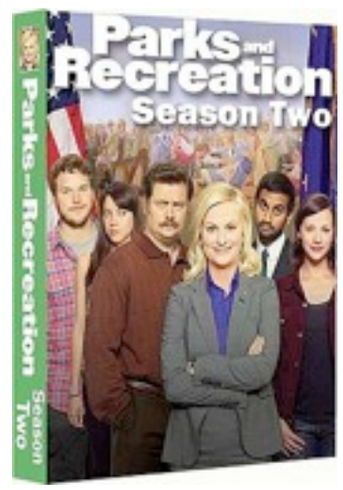

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  - KABooM, a program that calculates abundance of dark matter particles .....???

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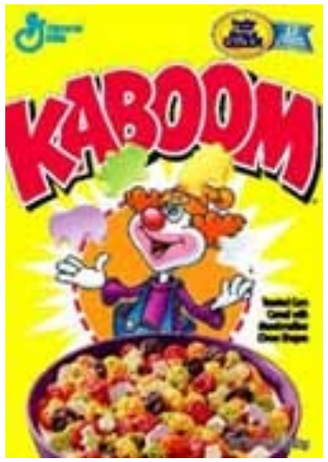

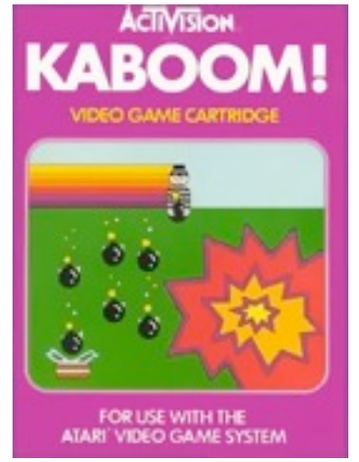

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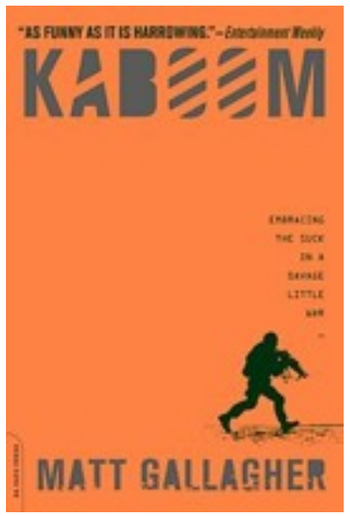

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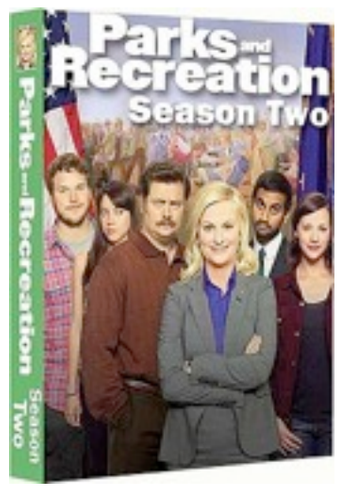

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Summary

- We have motivated the potential use of a DM tool in the MadGraph 5 framework
- Current version agrees well with other similar programs (relic density)
- More validation is being done
- Plans for more features
  - Suggestions are welcome!
- Publicly available this Fall